Toward an Algorithmic Realism: The Evolving Nature of Astronomical Knowledge in Representations of the Non-Visible

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ABSTRACT

This paper explores the gathering of radio, optical and electromagnetic wavelength data in assembling images of the Crab Nebula (1844–2000). The author considers the expanding fields of astronomical and astrophysical knowledge to which such data analysis has given rise. She suggests that the data that makes such imaging possible moves us further from conventions of the optical real toward an *algorithmic realism,* alluding to time-scales that delimit and circumvent human time. Thus Cartesian metaphysics is displaced—the human becomes one agent among many in a process of algorithmic inference.

Recent photorealistic images of astronomical objects are illustrations of compiled datasets, cross-referenced from numerous sources. These datasets are often readings of wavelengths from the electromagnetic spectrum, beyond the capability of human vision. The electromagnetic spectrum consists of all known wavelengths of light, from radio to gamma radiation, allowing scientists to detect, for example, the chemical composition of matter or the temperature of a star [1]. While telescopes were originally based upon the fixed perspective of a static, monocular human visual system, some are now designed to gather information across all wavelengths by various means.

The photographic image references a Western metaphysics dating back to Descartes. Divisions between the subject and object evinced by the photographic image are undoubtedly perpetuated by the invisible technical supports that mask the contingency of the image in seeming to bear witness. In a snapshot photograph, the image might be considered an index of the photographer's bodily location in time. While astrophotographic images may bear the aesthetic of the photograph, they depict objects that cannot be seen with the naked eye, across magnitudes of time where physical proximity is not possible. Regardless of the remoteness of the physical object, it is astronomy-grade charge-coupled devices (CCDs—the light-sensitive silicon chips used in all digital cameras), rather than snapshot photographs, that present a linear, quantifiable relation between what is sensed and the recorded result. Because CCD data are measurable they can be said to be *continuous* with the subject matter they represent in ways that the snapshot is not.

As an example of the developing complexity of image construction, let us look at images of the Crab Nebula made between 1844 and 2000 and the way in which these images reflect astronomical and astrophysical speculation.

Barthes once referred to the analog camera as *a clock for seeing* [2]. In measuring vision by fractions of a second, the camera consolidates the relationship between human time-based perception and its "object" as a finite, "real" one. Today, we can apply such an idea to optical, nonoptical and radio telescopes. Indeed, data collated from the Crab Nebula's pulsar allows scientists to measure time in milliseconds. However, I posit that the amassing of data that makes such imaging possible moves us further from conventions of the optical real (such as photorealism) toward an *algorithmic realism* [3] that alludes to "indifferent coordinates whose zero point is no longer the human being" [4].

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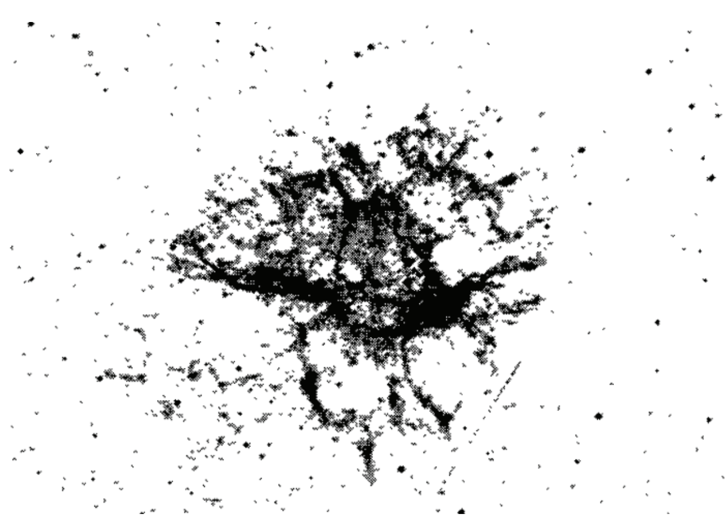

Fig. 1. G. Münch, spectroscopic emission line image of the Crab Nebula, 200 in, Hale Observatories, 1958. Originally published as Plate IVc in Davies and Smith, eds., *The Crab Nebula: The International Astronomical Union Symposium.* No. 46 (D. Reidel, on behalf of IAU, 1971). (© IAU <www.iau.org>)

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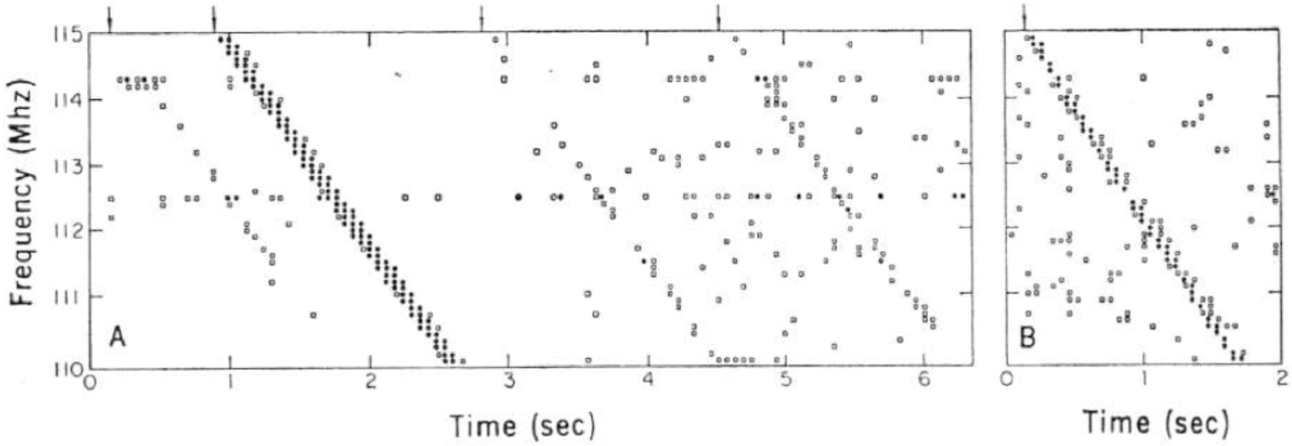


Fig. 2. D.H. Staelin and E.C. Reifenstein, Radio Pulse of NP 0532 and NP 0527, 1968. From David H. Staelin and Edward C. Reifenstein, "Pulsating Radio Sources near the Crab Nebula" *Science*, 27 December 1968, Vol. 162 no. 3861, pp. 1481–1483 DOI: 10.1126/science .162.3861.1481. Reprinted with permission from AAAS. <https://www.sciencemag.org/content/162/3861/1481.abstract>

Detection

Let us begin by looking at the way in which the Crab Nebula has provided an object of engagement and speculation for astronomical and astrophysical communities.

The ability to look further and more clearly into the cosmos is coupled with the ability to look further back in time. The Crab Nebula is the remnant of a supernova explosion (the radiation energy from the death of a star) visible from Earth in 1054 AD, as documented by Japanese, Chinese, Middle Eastern and European astronomers.

During the 1920s, observations revealed the Crab Nebula to be expanding at 930 miles per second—equations could be reversed to show that expansion had begun 900 years previously, correlating with earlier sightings [5]. The Nebula is considered the first known astronomical object related to a supernova and the first supernova discovered to have a neutron star (or pulsar) at its center—the latter having been predicted ahead of its discovery by Hoyle et al. and Pacini [6]. The existence of the condensed, rapidly rotating pulsar at the center of the Crab Nebula's mass was also predicted in 1934 but thought beyond the possibility of observation due to its diminutive scale and light [7]. Trimble (1968) first measured the proper motions of its nebular components, combining these with Munch's 1958 spectroscopic data to more accurately locate this tiny point in the past [8] (Fig. 1). The Crab Nebula is now known to be about 6,500 light-years away and continually expanding, eventually to disappear "like a puff of smoke in slow motion" [9].

Pulsar astronomy would open onto a new field of techniques for astronomical

Fig. 3. E.M. Kellogg, measurements of Crab Pulsar's spectral index, 1970. Originally published in Davies and Smith, eds., *The Crab Nebula: The International Astronomical Union Symposium.* No. 46 (D. Reidel, on behalf of IAU, 1971). (© IAU <www.iau.org>)

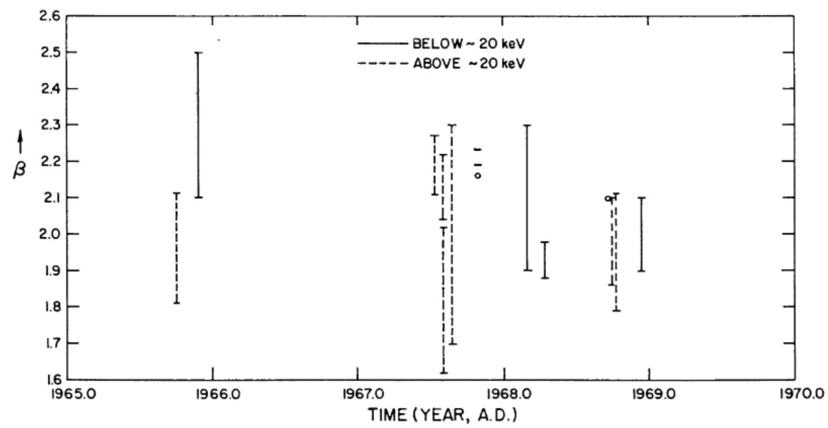
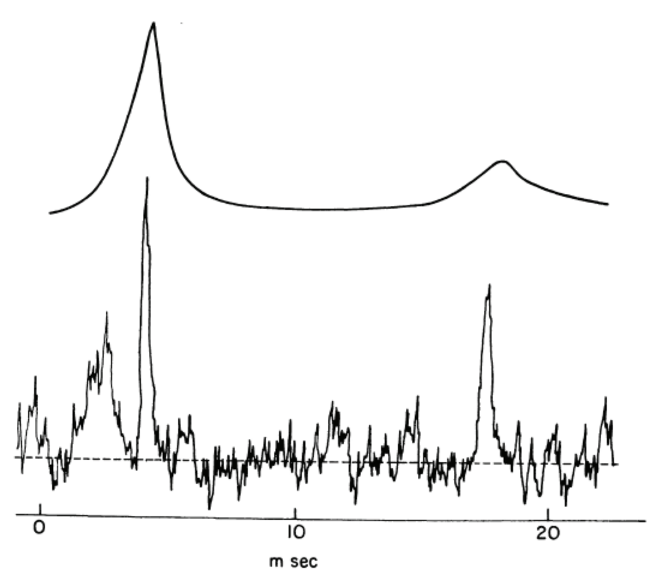


Fig. 4. J.M. Rankin, P. Horowitz, C. Papaliolios and N.P. Carleton, in F.D. Drake [17]. Below, observed average radio pulse shape of NP 0532 at 430 MHz; above, average optical pulse shape. (© IAU <www.iau.org>) Originally published in Davies and Smith, eds., *The Crab Nebula: The International Astronomical Union Symposium.* No. 46 (D. Reidel, on behalf of IAU, 1971).



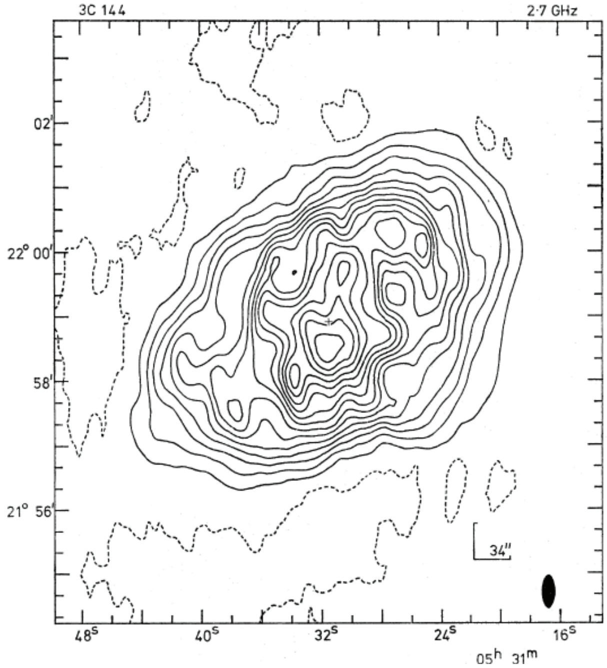


Fig. 5. A.S. Wilson, radio telescopic data, radio intensity at 2.7 Ghz, Wilson Observatory, 1972. "The Structure of the Crab Nebula at 2.7 and 5 GHz-I," ***Monthly Notices of the Royal Astronomical Society,*** **Vol. 157, No. 3, p. 231 (1972). Published for Royal Astronomical Society by Blackwell Scientific. (© RAS)**

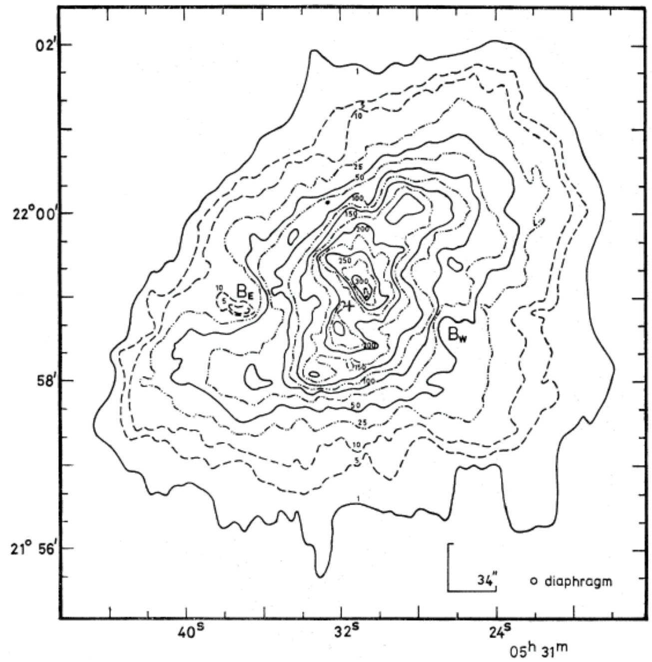


Fig. 6. L. Woltjer, Isophotes of optical continuum intensity (1957). "The Structure of the Crab Nebula at 2.7 and 5 GHz-I," ***Monthly Notices of the Royal Astronomical Society*** **Vol. 157, No. 3, p. 233 (1972). Published for Royal Astronomical Society by Blackwell Scientific. (© RAS)**

discovery and astrophysics. Pulsars were first detected via radio array in 1967 by Jocelyn Bell, while she observed interplanetary scintillation [10]. The appearance of regular interference on radio data was caused by radio waves produced by a rapidly rotating neutron star [11]. Radio telescopes can determine that which is beyond the scope of an optical device. The first rudimentary model was developed by Reber in 1937, and although resolution was once rather weak, it has been improved by recent technologies such as the digital correlator, the atomic clock and sophisticated image processing algorithms [12].

The Crab Pulsar was first detected in radio by Staelin and Reifenstein in 1968 (Fig. 2). That pulsars might emit pulses of light as well as radio waves was first tested and observed in the same nebula in 1969 by Cocke et al. [13]. A majority of pulsars are observable only by radio pulses, which can be highly variable, sometimes being deducted by collation of hundreds of observations [14]. The number of photons detected per pulse may vary significantly in results from gamma rays or large optical telescopes—however, precise timing over long periods allows detection of interval and overall profile [15].

Figure 3 shows some of the first selected measurements of the Crab's X-ray spectral index taken by rocket and balloon between 1965 and 1970. The unbroken lines show sounding rocket measurements, while the dotted lines show balloon measurement.

Such observations revealed that the X-ray region radiated power at least 100 times that of visible light and that pulses matched the same profile as optical and radio signals [16]. In Fig. 4 we see the radio pulse at 430 MHz; the shape is the mean of many thousands of pulses [17]. Above it, the optical pulse shape is also demonstrated, and Drake would conclude that these processes certainly occur in the same material, although not necessarily in the same physical process [18]. The parity between radio and optical data is seen again in Figs 5 and 6, the first showing radio data mapping intensities that radiate outward from the pulsar, which is marked with a cross in the middle. The data in Fig. 5 was gathered from the 1-mile telescope in Cambridge, U.K., between March and May 1970 [19]. In Fig. 6, we see isophotes of the optical continuum. Isophotes are lines on a diagram or image that connect, or map, areas of constant brightness.

The development of gamma ray astronomy in the early 1970s provided a high-energy regime in which pulsars could also be detected [20]. The shape of the pulse was almost the same as seen in previous data [21]. Figure 7 shows the pulse profile of signals from the Crab Pulsar across the spectrum, from radio wavelength to optical, X-ray and gamma ray.

Spectrophotometry selects a number of wavelength ranges, allowing astronomers to compare intensity variation at selected wavelengths, revealing physical and chemical processes as well as producing data concerning the object's origin and evolution [22]. Thus, division into selected sub-ranges of the ultraviolet, optical or infrared regimes is achieved using filters, producing a black-and-white image for each selected spectral range [23]. The spectrum of the Crab Pulsar is unique—observable over 18 orders of magnitude across the entire electromagnetic spectrum and visible almost continuously, from radio at 30 MHz to rays at above 100 GeV, the widest known range for an astronomical object [24].

Spectra used to depict the velocity of the Nebula are summarized from over 300 estimates in Fig. 8 [25]. These graphs were eventually combined with other data in a 3D image of the Crab's structure. In the final composite image, pixels represent the largest radial velocity value from each summation of data where different values were obtained [26]. Blueshift data (blue/green pixels in the image) show us the approaching near

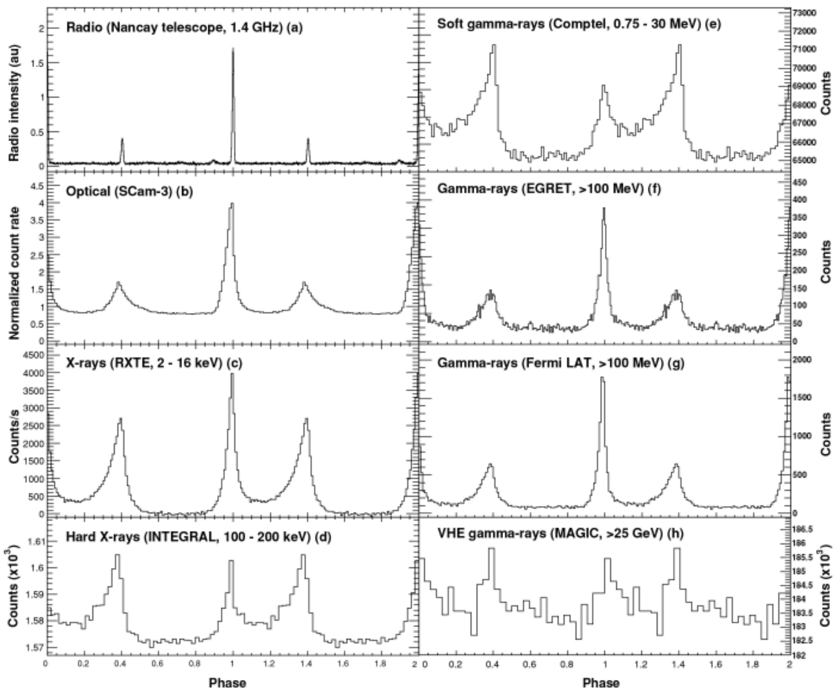


Fig. 7. Aous Abdo, M. Lemoine-Goumard, M.N. Mazziota, M.-H. Grondin, F. Loparco et al., Pulse profile of Crab Pulsar, radio to gamma, 2010. Originally published in Aous Abdo et al., "Fermi Large Area Telescope Observations of the Crab Pulsar and Nebula," ***Astrophysical Journal*** **708 (2) [1254] (2010) p. 5, IOP Publishing. (© M. Lemoine-Goumard, A. Abdo, M.N. Mazziota, M.-H. Grondin, F. Loparco et al.)**

side, while redshift (yellow/red pixels) show the receding far side of the object.

Between 1958 and the present, technology has improved by several orders of magnitude, not only in its sensitivity (units of energy per square meter) but also in its frequency coverage (from radio waves to gamma rays), in frequency resolution, and in information processing rate.

Astrophysicists continue to expand knowledge of matter through pulsar astronomy. In 1987, physicists realized that radiation from supernovas also contained a pulse of *electron antineutrinos* [27]. Neutrinos are subatomic particles produced by decaying radioactive particles, themselves lacking an electrical charge.

Recently it has been suggested that neutrinos from a supernova could serve as gravitational wave detectors, allowing physicists to narrow down the uncertainty of gravitational wave arrival [28]. Before a dying star explodes, it is thought that neutrinos are produced from nuclear reactions, carrying away 99 percent of the supernova's radiated energy [29]. As neutrinos barely interact with matter, most particles reach earth in advance of the event. Recently, advanced neutrino detectors have been made available, alongside laser gravitational wave detectors [30].

Thus we see the way in which astronomical detection has led to new realms of astrophysical inquiry, as well as expanded measures of time and space. Such data-collecting techniques allude to algorithmic coordinates whose timescale and visible range are increasingly beyond that of the immediate human sensory experience. In this sense, human agency is one among multiple agents engaged in algorithmic verification of data.

Imaging Science

Here we look in detail at the collation and construction of astronomy images, evaluating their photorealistic appearance in relation to original datasets and intended purpose. Since the early days of the telescope, when the images produced could be said to be *photographs*, imaging has evolved to become rather a representation of the science itself [31].

In astronomy images, it is normal to assign "representative" color to multiple datasets within a single image, depending upon the data to be used and the science to be illustrated [32]. These developments are in line with the digital programs used to edit images. For example, Photoshop allows for the layering of images so that separate datasets can be individually assigned and color superimposed and retouched accordingly [33]. Using layers for dataset color assignments allows the scientist to separate narrow wavelength ranges that may, for example, have the same chromatic wavelength. That is to say, different images capture light from distinct wavelength ranges, but these ranges are classified as belonging to the same broader wavelength regime, associated with one specific color [34]. Layering allows for consideration in creating convincing spatial depth, motion, temperature and emphasis within the final composition [35].

Latter-day astro-imaging is inextricable from the history of the photographic process, having first employed photographic plates and now using electronic detectors that take the form of highly sensitive CCDs. Indeed, mobile technologies such as cameras, projectors and telephones have greatly benefitted from the ubiquitous development of astronomy-grade CCDs [36].

Digital images are encoded by "uniformly subdividing the picture plane into a finite Cartesian grid of cells . . . or pixels" [37]. In the case of astronomy-grade CCDs, the intensity value of each pixel is a measurement. Each photon of light striking the CCD is converted into a number of electrons that can be counted within efficiencies of approximately 70 percent, as opposed to the 2 percent average of photographic plates [38].

CCD images generally contain a linearity of 1 percent across a range of values [39] and can thus be used to present continuous data; that is to say, they are analogues of the matter they detect via radiation. One percent linearity may seem small, but the human visual system itself is not linear, our eyes making approximations rather than linear measurements. For example, two lightbulbs illuminating a small room may not seem to make the room twice as bright, even though this is the measurable case [40].

The refinement and difference in efficiency in gathering photons of light can be demonstrated in Figs 9–10 and Color Plate C Nos 1 and 2, showing depictions of the nebula over the years 1844 to 2000. Figure 9 is a drawing made by hand in 1844, using a 36-inch reflector to assist the eye, while Fig. 10 shows an optical photograph also made with a 36-inch reflector between 1898 and 1900, this time, the Crossley Reflector of the Lick Observatory.

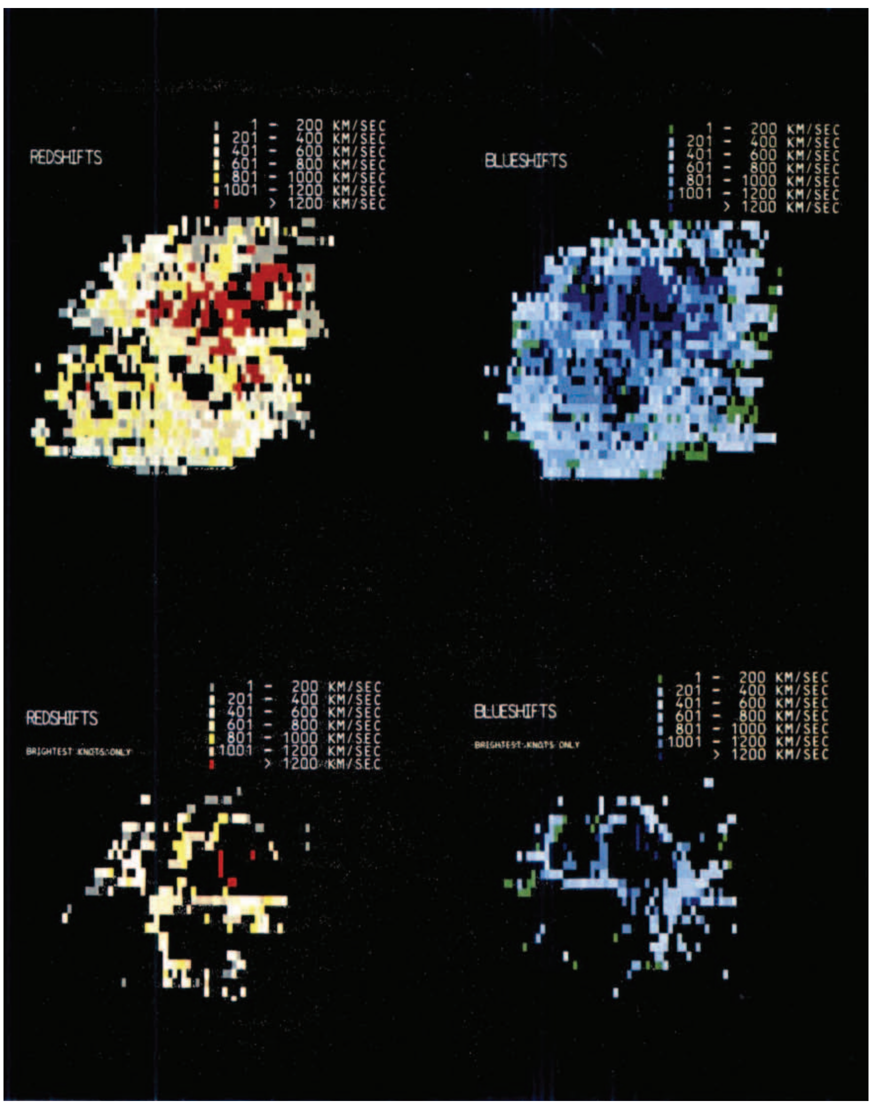
Color Plate C No. 1 was created by David Malin in 1990, using negative plates originally made in 1956. Malin developed a combination of film and filters, intending to show what the eye would see were it as sensitive as the specialist film used. Its spectrophotometry continuously covers the range of the visible spectrum and traces physical properties; as such it comes closest in presenting a detailed view of the phenomena as it might appear to the human eye [41].

The Malin image is dominated by pinks from ionized hydrogen, sulfur and nitrogen, whereas in Color Plate C No. 2, selected light is largely produced by ionized gas, and colors are more variously assigned [42]. The light contrast and sharpness are heightened dramatically, enhancing a sense of photorealism that situates the object as part of this familiar aesthetic tradition. The image is cropped in such a way that we are almost literally moving closer, beyond the surface of the picture plane and into the object itself.

The camera responsible for much of Hubble Space Telescope's (HST) imaging (see Color Plate C No. 2), and with whose results we are most familiar, is the Wide Field and Planetary Camera (WFPC 2), whose mirrors focus and reflect light to CCDs. HST's public outreach images of universal phenomena rely upon a referent that remains unseen and unseeable to the human eye, representing a view into the astronomical past, sometimes across billions of light-years. The objective of such outreach images is to present and illustrate scientific data in a compelling and interesting way for both the scientific community and the public. As such, these images are intended to illustrate an object's physical properties [43]. That HST's cameras should produce images of public appeal was a prerequisite of its construction [44]. However, this facility should not compromise the nature of scientific information and data produced, such images being illustrations of scientific content. Color Plate C No. 2, taken using WFPC2, was also produced using spectrophotometric data, but, in contrast to the Malin image, used filters that do not continuously span the optical wavelength range. The color in Color Plate C No. 2 indicates different elements expelled during the explosion, "blue in the outer filaments represents oxygen; green is singly ionized sulfur; bluish interior light represents accelerating electrons" [45]. These subsamples are collated and combined in layers, creating composite images that in themselves are not measurements. This image comprises several observations during 1999 and 2000. As such, we might say that it mirrors the construction of this paper—a process of *grammatisation* [46] via technical supports of existing data collation and feedback from readers; a collection of discrete elements gathered as seamlessly as possible into one piece of writing. This text would not exist without databanks of images, the careful archiving of library materials, astronomical tools and astronomers to gather the data, etc. The objective in both cases is to make the result seem continuous by making the technical supports upon which either relies invisible. The "reader"'s ability to participate in the final meaning of the work contributes to a narrative free of the technical actors that perform it. As such, we can see the image as a Latourian black box that masks its internal constituents—a potentially infinite regress of networked and abstracted actors [47].

The sequence of images allows an increasingly clear view of the structure—an approach. In the final composite image (see Color Plate C No. 2), our gaze penetrates the web of this dense astronomical mass, in a continuation of the journey that began in the plate photograph from the Lick Observatory [48]. It is as though we are gradually peering into the body of a prone subject, from a position that allows us to entirely command the spectacle from the edge of its surface. This visual trajectory suggests an observer whose physical relation to the object changes over time—facilitating an increasing depth of field, moving ever closer to the object's constituent internal structure in a manner that echoes the historical explication of human anatomy. In this regard, we might also consider 10-second animated sequences of the pulsar within the Crab Nebula [49]. The image's red glow and unintentionally grainy, incomplete assembly evoke sonographic imaging of the human fetus, referring not only to the mapping

Fig. 8. D.H. Clark, P. Murdin, R. Wood, R. Gilmozzi, J. Danziger and A.W. Furr, Plate 1. Colorgraphs constructed from the data in the tables in "Three Dimensional Structure of the Crab Nebula" in *Monthly Notices of The Royal Astronomical Society* 204: 1 (1983) p. 416A. (© David H. Clark)



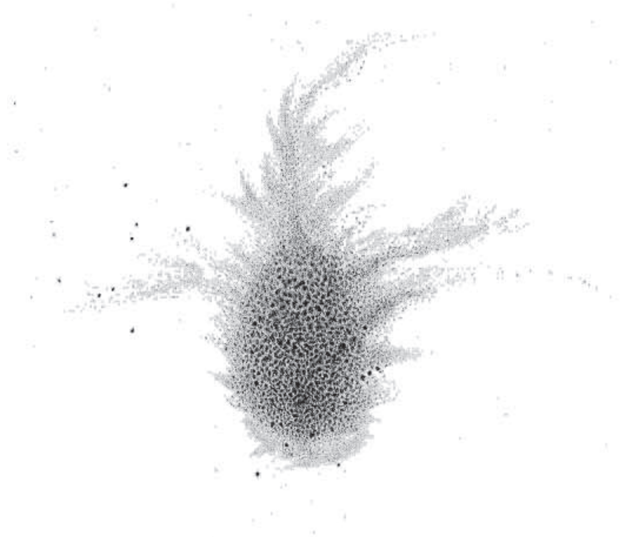


Fig. 9.
Lord Rosse, *The Crab Nebula*, drawing using 36-inch reflector, 1844. (© Royal Astronomical Society)

Fig. 10. James Edward Keeler, Crab Nebula, optical photograph made with 36-inch reflector between 1898 and 1900, published in James Edward Keeler, "Photographs of Nebulae and Clusters, Made with the Crossley Reflector," *Publications of the Lick Observatory*, Volume III, 1908.

of bodies but to geopolitical, economic and historical dimensions [50]. The historical passage that these images chart encompasses developing technological paradigms and shifting attitudes not exclusive to astrophysics and time. The data has been through a constant process of probability assimilation—cross-referenced like the information regarding pulsars we saw above. Key to the construction and assembly of the HST image is what might be termed an *algorithmic realism,* in which actors execute algorithmic procedures that layer components into a final speculative image.

We perhaps tend to think of an algorithm as purely referring to software or digital computation. Galloway refers to the algorithm as "a machine for moving parts" [51], inferring a broader definition of both algorithm and machine. Indeed, Lacan noted that language itself is algorithmic—an automated and axiomatic system [52]. In this manner, humans too are capable of behaviors that are both (but not limited to) algorithmic and machinic. More radically still, Luciana Parisi sees algorithms as entities imbued with infinity—quantities of data at once actual and abstract [53]. No longer "simply instructions to be performed," they "have become performing entities: actualities that select, evaluate, transform and produce data" [54].

In seeming to come closer to the image, we are simultaneously removed by an increasingly complex and contingent number of actors that participate in the image construction. This reflects the increased perception of deep space that coincides with the ability to define time at the nanoscale. Much like the illustration of web page graphics that mask other numerical, algorithmic structures, the surface of the visual image and indeed the visual itself represent but one *layer*, to borrow a familiar software metaphor. Here, it may be helpful to consider the *stratification* of layers, in which none is fixed or has greater significance than any other, in order to counter notions of surface and depth, where surface is usually associated with a lack of substance. Such ideas compromise close analysis of the material, suggesting an uncertain and underlying meaning. That is, methodological explication is compromised by metaphysical obfuscation, reinstating idealist distinctions between depth and surface, inside and outside. Images as representations of various time-scales (as "clocks for seeing") give rise to increasingly complex epistemological summations that allude to time beyond human construction—to a visual system limited by the brief periodicity of the human animal and the timescale of its cellular regeneration.

Critical Points and Conclusions

In the astronomical objects depicted in this paper, notions of *observer* refer not simply to the seen but to data from non-visible wavelengths and radio waves. Thus we can usefully apply the Latin origin of the term *observare* (to comply or conform with) in terms of the word's intended origin—as a process whereby data sets refute one another in a system of continual comparative evaluation [55]. The *viewer* participates in isolating an instance from an infinitely more complicated network of algorithmic actors that facilitate apprehension of new magnitudes of time and space—and so participate in the construction of an *algorithmic realism.* In so doing, we might think of Meillassoux and Gironi, for whom

> the process of mathmatisation is not simply a useful heuristic tool for scientific theorising or a means for technical control of nature, but opens up a completely new view of the universe, revealing a "*glacial* world" organised according to a set of indifferent coordinates whose zero point is no longer the human being [56].

Acknowledgments

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